PRODUCTION OF O₂ ON THE MOON: A LAB-TOP DEMONSTRATION OF ILMENITE REDUCTION WITH HYDROGEN. Lawrence A. TAYLOR¹, Eric A. JERDE¹, David S. MCKAY¹, Michael A. GIBSON², Christian W. KNUDSEN², and Hiroshi KANAMORI³. ¹ = Planetary Geosciences Institute, Dept. of Geological Sciences, Univ. of Tennessee, Knoxville, TN 37996; ² = Carbotek Development Laboratories, Houston, TX 77084; ³ = Shimizu Corp., Space Projects Office, Tokyo, Japan.

Estimates of the costs of transporting materials from Earth to the Moon are around $25,000 per pound. Therefore, it is imperative that we learn to utilize the resources on the Moon to partially offset these "astronomical" expenses. The production of oxygen on the Moon utilizing indigenous materials is crucial to the establishment and development of an autonomous lunar colony. Besides obvious biologic needs, this lunar liquid oxygen (LLOX) could result in tremendous cost savings on fuel for effective transportation systems, particularly with its export to low-Earth orbit. Over 20 different process concepts have been proposed and evaluated for the production of oxygen from lunar materials [1-3]. Simplicity, low energy, easily attainable feedstock, and low resupply mass are the keywords for the process(es) which will ultimately be selected for the initial production of oxygen on the Moon. One of these schemes, which has received considerable study to date, is the hydrogen reduction of ilmenite. In fact, Carbotek, Inc. (Houston, TX) has patented an ilmenite, hydrogen-reduction technique involving a three-stage, fluidized-bed process for the production of LLOX [4]. This abstract explains a lab-top demonstration unit of the basic concepts of this oxygen generation process that has been constructed by our group at the University of Tennessee. It utilizes many of the principles which must be addressed in designing an effective production plant for operation on the Moon.

The fundamental equation that most easily explains the chemistry of this process is:

\[ \text{FeTiO}_3 + \text{H}_2 = \text{Fe} + \text{TiO}_2 + \text{H}_2\text{O}; \quad \text{H}_2\text{O (electrolysis)} = \text{H}_2 + \frac{1}{2}\text{O}_2 \]

Hydrogen reacts with ilmenite to produce native iron (i.e., zero-valence) and titanium oxide and water, which is electrolytically split to form oxygen and hydrogen, which is recycled. Oxygen is then cryogenically liquefied to make LLOX. The amount of LLOX that can be obtained by this process is greater than 10 wt% of the ilmenite reactant. Actually, it can be several percent more, since the TiO₂ is effectively reduced to a less oxygen-rich titanium oxide species.

In addition, it should be possible to process the Fe + TiO₂ product and effectively liberate the Fe for recovery as an additional by-product. It is anticipated that the initial hydrogen will be brought from Earth; however, it is possible that little additional hydrogen make-up (i.e., resupply mass) will be necessary from Earth. This assumption is based upon the establishment of a ready source of hydrogen on the Moon. Lunar soil contains abundant hydrogen (50-100 ppm), and other solar-wind particles, which have impinged upon, penetrated slightly (<200Å), and are lightly held on the surfaces of each soil particle [5]. In fact, lunar ilmenite in the soil acts as an effective "sink" for solar-wind particles, and this ilmenite can contain up to 0.1 wt%. This ilmenite-hydrogen in itself will supply about 10% of the mass needed for complete reduction. If a lunar soil is used for feedstock with little real beneficiation, additional hydrogen input will be realized from the surfaces of the various silicate mineral and glass particles. In fact, a resupply need of 10-20% should be entirely offset by this solar-wind input.

A schematic flow diagram of our lab-top demonstration model is given in Fig. 1. We want to emphasize the simplistic, self-contained nature of this unit. The ilmenite feedstock (pure FeTiO₃ with only Fe²⁺) is placed into the silica-glass tube within the furnace. The system is flushed of air by use of a balloon of H₂ and the switching of valves while the H₂ is flowing such that the air and H₂ is collected in a flush-receiving bladder. A fresh balloon with about 3 liters of H₂ is attached to the system and stable hydrogen circulation is measured by a calibrated flowmeter. A peristaltic pump has two functions: 1) to pump cooling water to the condenser on the out port of the pear-shaped collection flask; and 2) to effectively circulate the H₂ (and H₂O) gas through the system.

The furnace is turned on and reaches 1000°C is about 0.5 hours. The circulating H₂ reduces the ilmenite, forming water vapor that is also carried along with unreacted H₂. The water vapor is either a) condensed out into the pear-shaped flask or b) scrubbed out by absorption into the drierite in the U-tube. In reality, a portion of the H₂O vapor stays as gas, thereby decreasing the effectiveness of the H₂ reduction process (the H₂O causes an increase in $fO_2$ of the reducing gas). This illustrates an extremely important concept that must be well-addressed in the actual lunar production plant, namely the efficiency of the extraction of H₂O from the system. The kinetics of the ilmenite reduction depend directly upon the $H_2/H_2O$ ratio in the reducing gas -- the higher the ratio, the faster and more complete the reduction. If the mole fraction of H₂O in the gas stream passing over the sample exceeds about 10% at 1000°C, the reaction will be at equilibrium and further reduction will stop. Consequently, it is extremely important to keep the H₂O mole fraction low in the reacting gas.

Using about 20 gm of pure ilmenite as our charge, it was possible to obtain almost 1 cc of condensed H₂O. The remainder of the H₂O produced was absorbed by the drierite, which could be seen to get a pinkish color, particularly at the leading side of the U-tube. In 1.5 hours from the start of the demonstration (about 1 hour at temperature), the ilmenite was observed to be >95% reduced. The kinetics of reduction are fast even in the presence of the small amount of H₂O in the reducing gas. Of course, the kinetics are not as fast as when an open system is used with pure H₂ [6]. The balloon supply of H₂ decreased by about 2 liters, the amount that was converted to H₂O.

We have constructed a "science-fair-like", lab-top demonstration unit for the reduction of ilmenite by hydrogen. We have stressed the self-contained, simplistic design of the entire system, with a total hardware cost of <$1000. It should be possible to make a similar unit into a compact flight package, for Artemis (?), for in situ experimentation on the Moon.